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ABSTRACT

The intention of this paper is to discuss the advances in thrust engines from the initial development of the J58/SR-71 (JT11D-20) of the U.S. Air Force's SR-71 Blackbird to the development of the RAM and SCRAM engines necessary to propel the new generations of high-flying super-speed aircraft. Engineering complexities suggest that the engines and their development cannot be fully discussed without referring to the airframe and the integrated design and manufacturing required for the aircraft. A description of the turbojet engine, the fanjet engine, SR-71 development, and the Scramjet system are included. A picture of the F110-GE-100 engine airflow is appended. (KR)

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A LAYMANS GUIDE TO
THRUST ENGINE DEVELOPMENT FOR SUPER/HYPER SONIC FLIGHT

Adapted from

A PRESENTATION AT THE 1991 ITEA CONFERENCE

" TECHNOLOGY EDUCATION IN THE SPACE AGE"

Salt Lake City, Utah

March 18 - 22, 1991

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Thrust Engine Development

The intention of this paper is to discuss the advances in thrust engines from the initial development of the J58/SR-71 (JT11D-20) of the USAF SR-71 Blackbird to the present development of the RAM and SCRAM engines necessary to propell the new generations of high-flying super-speed aircraft. Engineering complexities sugggest that the engines and their development can not be fully discussed without referring to the airframe and the integrated design and manufacturing required for the new aircraft. The new aircraft I refer to are the HSCT, the High Speed Civil Transport and the NASP, the National AeroSpace Plane. A combination of these vehicles was mentioned by President Reagan in 1986 in his State of the Union Address when he referred to a single mission aircraft, the "Orient Express", which could "take off from Dulles Airport, accelerate up to 25 times the speed of sound attaining low earth orbit, or fly to Tokyo within two hours". Present plans have separated that single mission into two aircraft designs.

Lets look at the conventional jet engines to bring everyone up to speed.

TURBOJET ENGINE

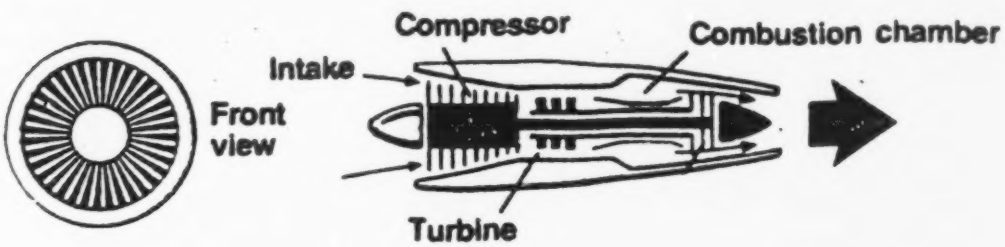


Figure 1 (Chicago Tribune, 1986)

2

The engine shown is an axial-flow turbojet engine. The air is brought in through the intake, compacted by the compressor section, passed through the fuel injection section where the compressed, hot air is mixed with fuel. It then flows into the combustion section where it is ignited and burned, and the hot gasses, greatly expanded, exhaust through the hot-section turbines and flow out through the ejector or tailpipe. Power for the compressor section is developed by the turbines located directly after the combustor and thrust is generated by the jet stream of the ejector or tailpipe.

FANJET ENGINE

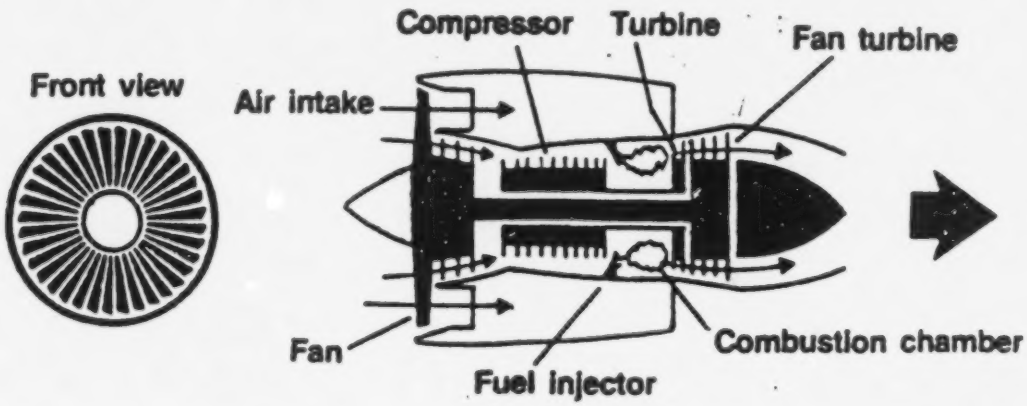


Figure 2 (Chicago Tribune, 1986)

The major difference between the fanjet and the turbojet is the large fan located immediately in front of the compresor section. Note that in the example above, the fan air is has two routes of flow, one into the engine's compressor and one which provides a flow-blanket of cool, partially compressed air around the main engine. The main engine is similar to the axial-flow engine shown earlier, with some subtle differences. The first is the addition of a turbine in the hot section to power the fan. The second

is a fan air duct leading directly into the hot section which induces fan air into the hot jet stream for additional expansion and thrust.

SR-71 Development

Before getting too deeply into the designs of the future aircraft, I would like to present the background on the SR-71 Blackbird. An old aircraft, to be sure -- it first flew during December 1964 -- and proved itself to be on the cutting edge of high speed, high altitude, aircraft development. Most new aircraft borrow designs, parts, engines or systems from their predecessors, the parameters for this aircraft were such that very few "hand-me-downs" were able to be used. A cruising speed of over Mach 3 (2000 MPH +) and a cruising altitude in excess of 80,000 ft. were the initial design requirements (Johnson, 1981). Most swift aircraft of that day were speed limited to Mach 2 for a short period of time, and the altitude limitations were generally around 55,000 to 60,000 ft. At that altitude, even the advanced engines would flame out for lack of oxygen.

Most airframes of that era were aluminum, and could withstand the ram-air temperatures generated by Mach 2 flight, but Mach 3 ram-air temperatures exceeded 800 degrees F at times and steady temperatures were 500+ degrees, eliminating aluminum as structural material (Johnson, 1981). Other heat resistant material had to be developed for the non-metallic surfaces, radomes, canopies and other structures. The X-15 flew faster and higher, but never more than a few minutes at a time, so continuous heating was not as critical. Aside from the skin and the other exterior surfaces, the interior of the aircraft had to be cooled from the incipient heat. Crew areas, wheels, tires and electronic equipment also

had to be cooled. Hydraulic fluid, electric wiring, engine lubrication fluids and other ordinary aviation items had to be re-thought and then redesigned. Even the fuel used required stability indexes from - 90 to over 350 deg. F. (Johnson, 1981).

The aircraft skin problem was settled using alloys of titanium and stainless steel. The fuel selected was a newly designed jet fuel which had to be raised to a temperature of 300+ deg. F before it would ignite, and it was essentially the only liquid used. It doubled as the hydraulic fluid for certain systems and as the coolant for skin, pilot station and other temperature sensitive areas. Other problems with metal forming, machine tooling and material bonding were overcome as they arose (Johnson, 1981).

The current production engines of that time were the J57 and the J75, used to power both USAF and USN fighter and attack aircraft. The J57 developed about 16,000 lbs. of thrust in full afterburner and the J75 developed slightly more in the same situation. Engine parameters for the two production engines and the projected requirements for the "Blackbird" are shown in Figure 3.

	J57 AND J75	JT11D-20
MACH NUMBER	2.0 FOR 15 MIN (J75 ONLY)	3.2 (CONTINUOUS)
ALTITUDE	55,000 FT	100,000 FT
COMPRESSOR INLET TEMPERATURE	250°F (J75 ONLY)	800°F
TURBINE INLET TEMPERATURE	1750°F (TAKEOFF) 1550°F (CRUISE)	2000°F
MAXIMUM FUEL INLET TEMPERATURE	110–130°F	300°F
MAXIMUM OIL INLET TEMPERATURE	250°F	550°F
THRUST/WEIGHT RATIO	4.0	5.2
MILITARY OPERATION	30-MIN TIME LIMIT	CONTINUOUS
AFTERBURNER OPERATION	INTERMITTENT	CONTINUOUS

Figure 3 (Brown, 1981 p.3)

The J58, one of the engines developed by Pratt and Whitney for the USN in 1956 for the F8U-3, was rated at approximately 26,000 lbs of thrust. It was to be used as the propulsion unit for an attack aircraft with a dash capability of Mach 3, but the project was scrapped when the USN contracted for a two place, twin engine aircraft. The J58 engine, designated the P2, had accumulated approximately 700 hours of full-scale engine testing by the time the SR-71 was in development. Because of the extremely hostile environmental conditions developed within the engine core, the only designs which could be used from the J58-P2 were the basic size and the aerodynamics for the compressor and turbine (Brown, 1981).

Though the designs from the J58-P2 were appropriate, the materials used in that engine were not. In his paper, J58/SR-71 Propulsion Integration - The Great Adventure Into The Technical Unknown, William H. Brown (1981) stated:

> "Fabrication and Materials technology presented one of the greatest challanges. We had to learn to form sheet metal from materials which had previously been used only for forging turbine blades. Once we had acheived this, we had to learn how to weld it successfully. -- I do not know of a single part, down to the last cotter key, that could be made from the same material as used on previous engines." (P-3).

The stability of the fuel posed a major problem in the starting sequence. An alternate fuel (tetraethyl borane, T.E.B.) had to be used to start the main engine and for igniting the afterburner. Another problem with the fuel was its lack of lubricity; fluorocarbon was added to provide

lubrication for the airframe and engine pumps and servos. The fuel, after having been used as coolant and hydraulic fluid, was unable to be cooled down, and, after one pass through the system, was burned (Brown, 1981).

Pressure spikes, inlet temperatures and volumetric flow were major problem areas in the beginning. Pratt and Whitney engineers develped a bleed bypass cycle and a movable fore-spike on the engine. This allowed management of the inlet airflow and a constant airflow at any given Mach number.

I mentioned integration of the airframe and engine. I would like to identify just a few of the problems faced during the on-going development of the SR-71 and the installation of the J58-JT11D-20 engine. First, early on in the program it was discovered that the gearbox mounts showed heavy wear and were cracking and the long gearbox drive shaft was twisting and the splines were wearing too quickly. It was ultimately discovered that the gearbox moved about four inches relative to the engine during high Mach flight due to structural heat expansion. The problem was solved by providing a new shaft with a double universal (Brown, 1981).

An engine mounting problem surfaced when it was found that, under certain wing down loads, the outer half of the engine nacelle would rotate into the engine and crush the fuel and high or low pressure lines. A redesign of the engine mounting system was completed to correct this (Brown, 1981).

Another problem was the high number of engine "unstarts". This was not a

flameout or blowout, the engine would continue to run at a slow speed and overheat. Inlet airflow was reduced to the point that the amount of fuel injected at idle was twice the amount needed to maintain RPM. One of the causes was identified as excessive nacelle leakage, reducing the 40:1 pressure ratio required. One solution was to adjust the airframe by sealing the leaks, another solution was to adjust the movable fore-spike to allow more air to circulate (Figure 4).

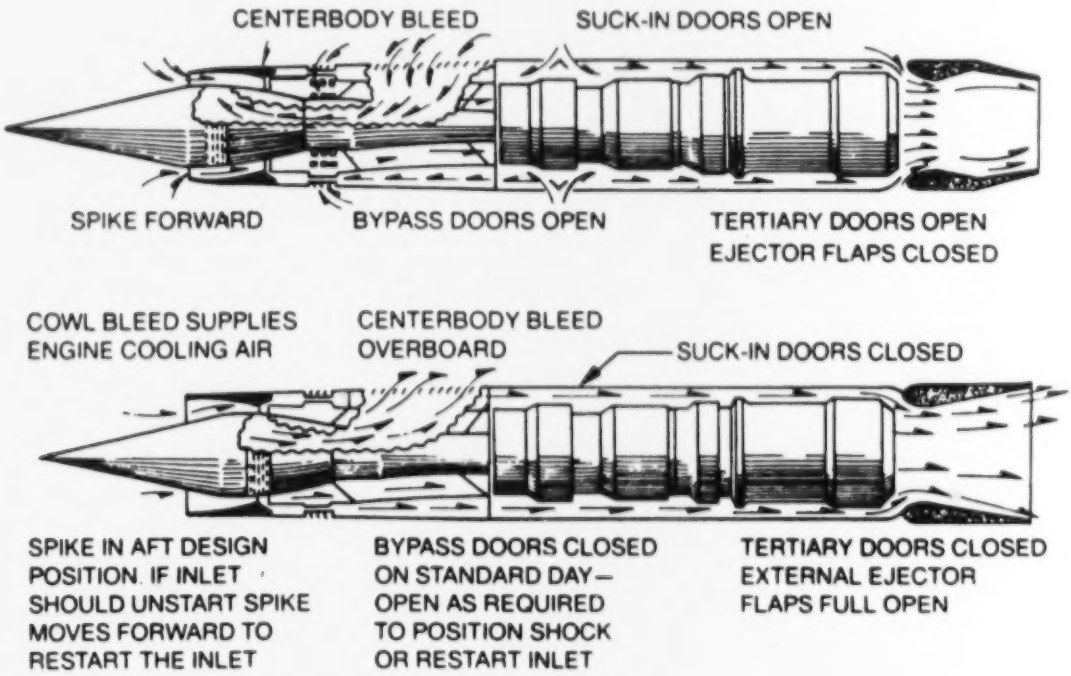

CENTERBODY BLEED
SUCK-IN DOORS OPEN
SPIKE FORWARD
BYPASS DOORS OPEN
TERTIARY DOORS OPEN
EJECTOR FLAPS CLOSED
COWL BLEED SUPPLIES ENGINE COOLING AIR
CENTERBODY BLEED OVERBOARD
SUCK-IN DOORS CLOSED
SPIKE IN AFT DESIGN POSITION. IF INLET SHOULD UNSTART SPIKE MOVES FORWARD TO RESTART THE INLET
BYPASS DOORS CLOSED ON STANDARD DAY— OPEN AS REQUIRED TO POSITION SHOCK OR RESTART INLET
TERTIARY DOORS CLOSED EXTERNAL EJECTOR FLAPS FULL OPEN

Figure 4 (Brown, 1981 p.5)

The information gleaned from designing and building the SR-71 has had a great impact on the aerospace industry. The composites developed, the tooling required, and the lessons learned in the use of high strength, high-

temperature resistant metals, computer simulations and wind tunnel testing have advanced the industry's capability to the point where the HSCT and the NASP are considered to be viable options.

Military engine development from the J58/SR71 to today's F110-GE-100 engine can be noted in Appendix A. Intake duct and compressor air flow slow the airstream to below Mach 1. The fan and compressor build up pressure and temperature in the airstream, resulting in an extremely oxygen dense, hot air flow. Please note the dual channel for the airstream after the fan stage. At that point, part of the fan compressed air is shunted into a burner bypass, still compressed and hot. The main airflow procedes through the compressor stage, becoming hotter and more dense, is inducted into the combustion section, mixed with fuel, ignited and ejected through the turbine section, providing drive power for the fan and compressor and thrust to propel the aircraft. The fan bypass air is used as a coolant and sound suppressor around the compressor, combustion and turbine sections and, in the augmenter mixer, part of the bypass flow is mixed with the hot core gas that has just passed through the turbines. In normal engine operation, this bypass air is heated and adds to the thrust output of the engine. The remainder of the bypass flow is diverted around the augmenter wall to provide a cooling flow.

During augmenter (afterburner) operations additional fuel is injected at the point of bypass flow core gas, mixed and ignited, providing additional thrust. As the augmenter is selected, the exhaust nozzle opens giving the additional burned gasses an adequate exit route. If the nozzle does not open, most augmentors will be automatically shut down.

The augmenter section on todays high performance engines is a close relative of the ramjet engine (Figure 5). The basic difference between them is that the augmenter on a turbo-ramjet engine is supplied with hot compressed air from the axial flow engine immediately upstream, the ramjet engine is supplied with hot compressed air by its movement through the atmosphere and the shape of the intake opening. The turbo-ramjet can be operated in a static situation, the ramjet requires initial high-speed movement to provide reactive thrust.

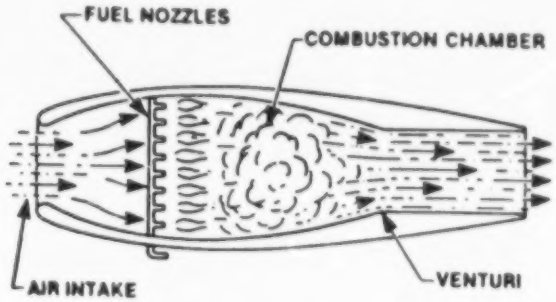


Figure 5

The J58 and the F-110 engines are adequate for aircraft propulsion up to Mach 3 +, internal temperatures required above that speed would disintegrate the engine parts. To arrive at the Mach 4 - 6 speeds desired in the HSCT, a ramjet engine will be required. Theory dictates that two distinct engines will be required to propel an airframe to speeds in excess of Mach 4, the turboramjet (J58/F110 type) and the pure ramjet. Compare the ramjet model with the F-110 model in the Appendix. No fan, no compressor, just an open, double venturi, fuel injector, ignitor, combustion chamber and ejector nozzle.

Actually, the present HCST engine designs, though not finalized, are headed

toward a combined-cycle engine, one that would initially operate as a turbo-ramjet to attain speeds of Mach 3+ and then operate as a ramjet to speeds of Mach 6+ (New York to Tokyo or LA - Sydney -- 2 hours. The Concorde, today's SST, travels from London to NY in 3 hours). A conceptualized design of a combined-cycle engine is shown in Figure 6. Note the design has the capability of closing off the turbojet portion of the engine to allow solo operation of the ramjet engine.

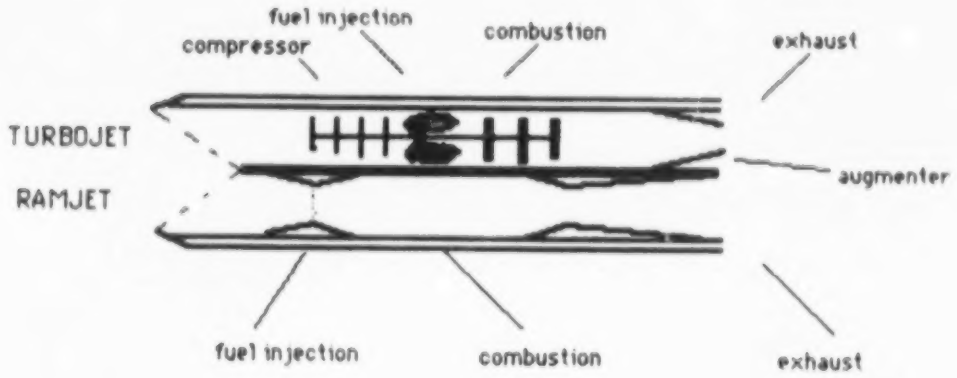


Figure 6

Engine/airframe integration will be as important in the design of the HCST as it was in the SR 71. Fuel used in the HCST will still be fossil fuel, perhaps the same fuel used in the SR 71.

SCRAMJET

Up to this point, the engines discussed all required subsonic air flow to allow combustion. The turbojet, the turbo-ramjet and the ramjet are unable to support supersonic combustion. At speeds in excess of Mach 3.5, the temperatures of the turbojet interior would exceed the heat resistance

of the materials and the engine would disintegrate. The ramjet partially overcomes this problem because of its fewer moving parts, but it is still speed limited at Mach 5 to 6. The answer is the scramjet, in which fuel can be mixed with supersonic air, travelling at approximately 1000 ft/sec at MACH 1 and ignited. This greatly delimits the time for ignition and combustion, posing a problem in fuel selection.

Fossil fuels currently in use do not have the appropriate properties for supersonic combustion, the fuel presently identified for use in this engine is liquid or slush hydrogen. Early studies on the scramjet (1960's) were set aside due to the lack of high-tech wind tunnels and computer modeling. Today's technology has provided the industry with the means to build and test mini-scramjets similar to the lower section of the engine shown in Figure 7 and to develop models which identify its potential to Mach 25, the speed required to attain orbital velocity (Siuru and Busick, 1987).

Scramjet designs are relatively simple, an intake, a mixing/combustion chamber and an ejector; a high speed ramjet, if you please. Simple, yes, but the technology for the materials and proof of the theory are difficult to attain. Present day test scramjets have operated at Mach 6 to 7 for micro-seconds, but at that speed, even a few micro-seconds of operation are adequate to prove the theory. Information on industrial development, particularly advanced industrial development, is difficult to attain. A conceptual model of a combined cycle turboram/scramjet is shown in Figure 7.

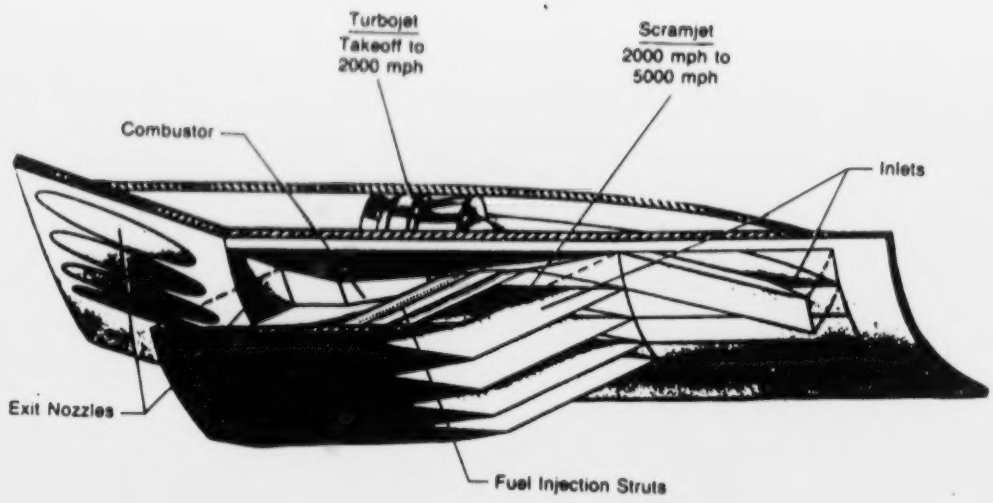
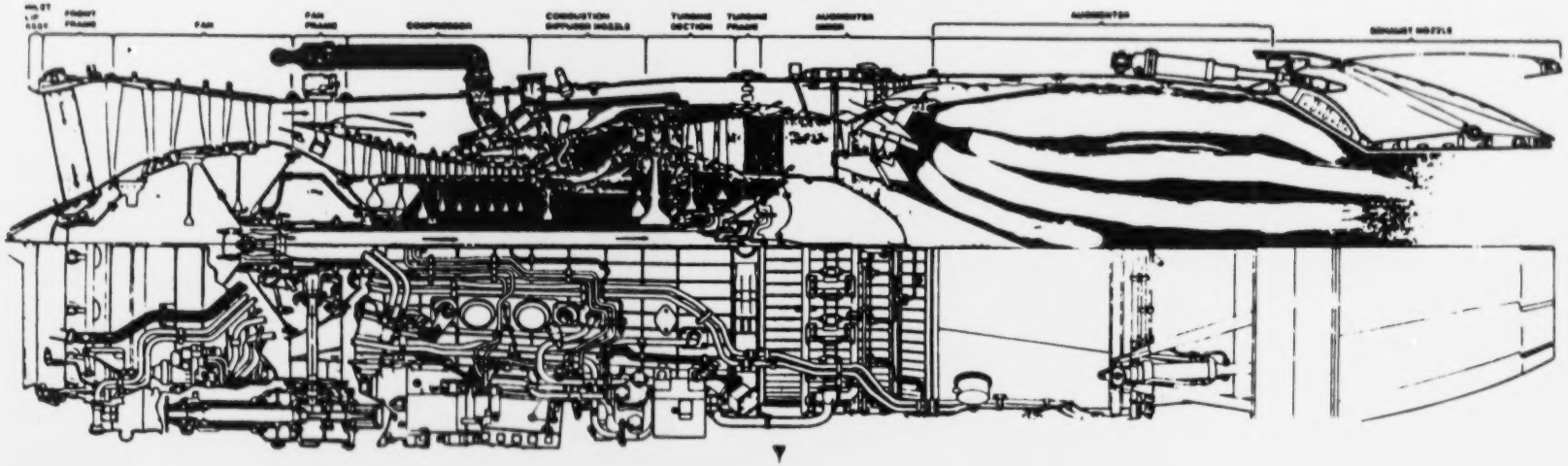


Figure 7 (Siriu and Busick, 1987)

Airframe development for these advanced aircraft will also require high-tech materials. The SR-71 and the space shuttle have provided a great deal of information on high speed surface heating and heat resistant ceramics which will be incorporated into the NASP materials. Many of these materials will be used in the airfames of the future. Artists concepts do not identify a large change in the "look" of the higher speed aircraft, perhaps more arrow-head shaped, more integration of engine and airframe during the design process, but in general, a form of standard airplane combined with a lifting body concept.

APPENDIX A

F110-GE-100 ENGINE AIRFLOW



GE, 198-.

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